Sound, Ecological Affordances and Embodied Mappings in Auditory Display

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Abstract

The third wave of HCI has seen the widespread adoption of design principles borrowed from and informed by breakthroughs in the field of embodied cognitive science. These developments have taken place primarily in the contexts of visual media and interaction, but they are also of importance to the design of auditory displays and interactive systems in which sounds plays a dominant role, where they open up new affordances by which information might be communicated to a listener. This chapter examines the relationship between auditory display, sonic interaction design and embodied cognition and explores frameworks from embodied cognition that might inform the design of more informative auditory displays in a variety of contexts. It will do so by addressing these issues from an interdisciplinary perspective, bringing together insights from cognitive science and philosophy, general HCI and computer science, and music theory and practice.

Introduction: Sound and its Affordances for HCI

Sound is a modality with a number of specific *affordances* (Norman 1988; McGrenere and Ho 2000) which a HCI researcher and practitioner can exploit. It can offer contextual cues to inform interactions whilst not requiring space within a visual interface. Our ability to recognise a wide variety of sound sources allows us to use a diversity of sound materials as cues, either in isolation, or in combination with visual cues. We also have a significant degree of sensitivity to difference between successive or evolving sound cues, supporting the use of sound as a 'display' technique in its own right, which can provide us with a means of exploring complex data. Moreover, the apparent tactility associated with sonic responses which are synchronised with particular interactions (for example, the 'key click' sounds associated with certain touchscreen interfaces to reinforce a sense of successful key activation based on their associations with the effect of depressing a key on a mechanical keyboard) draws our attention to sound's embodied affordances and the manner in which our experience of sound may be consistent with a *motor–mimetic* hypothesis for perception and cognition; see (Godøy 2003). The timbre or textural profile of particular sounds may have implications in terms of our senses of causal connections and semiotics in interactive applications, based on aspects of apparent physicality associated with certain profiles (e.g. high/low energy, stable/unstable, detached/sustained, etc.). Overall, sound's properties as a perceptual modality offer a number of potentials for enhancing our interactive experiences within a variety of application contexts, be they to support reasoning and interaction or the simple presentation of information to a listener. This chapter will explore these properties in relation to both auditory display and broader contexts of sound in interaction design. The question of theoretical framework is of critical importance when working with sound in an auditory display context. Different theoretical frameworks can open up novel design possibility spaces while simultaneously closing down others. Because sonification and auditory display are primarily concerned with making meaning from data, designers must use theoretical frameworks which can account for this kind of meaning-making. This chapter explores a number of such frameworks.

Section 1: Introduction to Auditory Display, Sonic Interaction Design and Mapping

Auditory Display and Sonification

Auditory display involves the use of sound to present information to a listener and *sonification* is a particular auditory display technique in which data is mapped to non–speech sound to communicate information about its source to a listener. Sonification can leverage the temporal and frequency resolution of the human ear, making it a useful technique for representing data that may be difficult to represent by visual means alone (Walker and Nees 2011). As we move further into the era of 'Big Data', sonification and auditory display techniques are becoming ever more important for representing and understanding complex data sets and structures (Rimland and Ballora 2013).

A variety of different definitions of auditory display and sonification have been offered as these fields have developed. *The Sonification Handbook* defines auditory display in broad terms, as any display that uses sound to communicate information, with sonification being treated as a subset of auditory display that represents information by mapping data to non-speech audio (Walker and Nees 2011). *The Sonification Report* (Kramer *et al.* 1997) defines the area slightly differently. It casts sonification as 'the transformation of data relations into perceived relations in an acoustic signal for the purposes of facilitating communication or interpretation.' These definitions have been instrumental in marking out the basic process involved in sonification and in guiding the direction of auditory display research.

The rigorously empirical spirit represented in Hermann's definition is of critical importance to the development of sonification research and practice. He argues that sonification is 'the data–dependent generation of sound, if the transformation is systematic, objective and reproducible, so that it can be used as a scientific method' (see Hermann 2008). An approach based on *design thinking* is introduced by Barrass who defines sonification as 'a mapping of information to perceptual relations in the acoustic domain to meet the information requirements of an information processing activity' (Barrass 1998, pp. 29-30). With the recent discussions around the role of *sonic information design* in auditory display research (Barass, *et al* 2018), this definition has come to the fore again in the area. Worrall (2009) sees sonification as 'the acoustic representation of data for relational interpretation by listeners, for the purpose of increasing their knowledge of the source from which the data was acquired.' This is an interesting definition that asserts the importance of the original phenomena (data source) in a sonification. A similarly important definition is that of Scaletti, who defines sonification as 'a mapping of numerically represented relations in some domain under study to relations in an acoustic domain for the purposes of interpreting, understanding, or communicating relations in the domain under study' (Scaletti 1994, p. 224). This simultaneously accounts for the 'hard' and 'soft' elements of sonification, acknowledging that it encompasses both formal mathematical concepts of representation and data transmission alongside the framing of data via mapping strategies which support humans in approaching the data via meaningful contexts. The definitions presented here represent only a small portion of those discussed across the literature; Supper (2014) explores the context in which they have been conceived in much greater detail. They are presented here because when considered as a whole, they offer an insight into the multitude of approaches and contexts within which sonification is situated by the research community.

An 'Embodied Turn' in Musical HCI and Auditory Display

More broadly, research in the fields of music technology, creative computing and digital arts is addressing sonic interaction design and the relationships between sound and the modalities of interactive systems, with active research communities engaged in designing new musical interfaces (e.g. the New Interfaces for Musical Expression conference) and sound's relationship with the broader computing field (including related work within the International Computer Music Conference, the Sound and Music Computing conference and the *Computer Music Journal*). Whilst initial research within the field of computer music was generally more concerned with technical developments within sound synthesis and signal processing than with interface modalities —an emphasis related in part to limitations in processing power, requiring early computer music languages such as Music N to be based upon a composition–production paradigm of coding (‘scoring’) and rendering (Wang 2007) —the 1980s saw the beginning of a concern for new performance modes within musical HCI and electronic music, concurrent with the development of the MIDI (Musical Instrument Digital Interface) protocol, which was an early standard for treating sound synthesis/audio processing and performance technologies as separate tasks; see (Mathews 1991; Roads 1996). In spite of these early developments in interface and performance technologies, the tension between sound production/processing and interface technologies was still present enough that Paine (2009) could still lament the comparative ‘disembodiment’ of the computer music field, noting perceptions of disconnection between performer, technology and audience. Roddy and Furlong (2013) have pointed out that part of the reason for this disconnect may also be related to a lack of ‘transparency’ in the conceptualisation of sound synthesis processes and parameters stemming from the absence of the human body in live computer music performance. There is a large community of researchers developing solutions for introducing the body to computer music performance and composition. Roddy and Furlong (*ibid.*) further note that ‘modern computer music is composed mainly using techniques and technologies that were developed for a disembodied representational mind that exists in a positivistic world’, citing Schafer’s (1977) ‘schizophonic’ divide arising from the technological decoupling of sonic or musical effect from physical/performative cause. However, in parallel with developing interests in HCI within the broader computing field, the 2000s has seen a significant degree of HCI–related work developing within the music technology and computer music fields. A notable feature of this work is its consideration of embodied structures on the basis of practice-based explorations of new forms of controller (Cook 2001; Tanaka and Knapp 2002; O’Modhráin and Essl 2004; Serafin and Young 2004; McPherson 2012), commentary on how performance gestures and affordances are treated (Jensenius 2014; Gurevich and Treviño 2007; Magnusson and Mendieta 2007; Hunt *et al.* 2002), and these relate to broader HCI frameworks (Wessel and Wright 2001; Wanderley and Orio 2002; Buxton 1987).

A key question which underpins both auditory display and the design of interactive systems is the mapping problem—how to organise the relationship between input and output—be it a data set (in the case of auditory display) or interface (in the case of sonic interaction design). Discussing such mappings in related to new instrument/interface design, Hunt *et al.* (2002) highlight the importance of the *mapping layer*, through a range of parameter mappings which range from simple (*one–to–one* correspondences) to complex (*cross-coupled* parametric mapping). They highlight how the latter can be conceptualised through (implicitly embodied) mapping relationships, such as *energy (of interacting gesture) controls brightness.* Wessel and Wright discuss musical interactions and mappings within the conceptual frame of 'intimacy', and specifically reference the field of *embodied cognition* as providing models for musical HCI (Lakoff and Johnson 1999), and Wanderley and Orio (2002) reference a target/gesture–based interactive framework from Buxton (1987), which is based on similar embodied discourses. Later work by Wilkie *et al.* (2010) applies embodied models even in the basic structural framing of WIMP–based musical interactions.

In order to more fully exploit the potential sound to represent complex data, auditory display researchers have also begun to explore new frameworks for working with sound suggested by research from embodied cognitive science; see (Diniz *et al*. 2010, 2012; Verona and Peres 2017). This 'embodied turn' is recent and still developing and a similar embodied turn is underway in auditory display research. The current chapter is intended as a guide for researchers who are interested in adopting insights from embodied cognition to auditory display and sonic interaction design.

Embodied Cognition and Sonic Information Design

Representative of this 'embodied turn' in auditory display research is the burgeoning field of *sonic information design*. This field has emerged in response to the increasing pervasiveness of embodied interaction and user experience in auditory display research. Sonic information design refers to the application of design research, defined by Faste and Faste (2012) as 'the investigation of knowledge through purposeful design, to auditory displays, auditory user interfaces and sonification.' In focusing on design this approach aims to enrich user experience as a whole, by considering the role of situated-acting, meaning-making, and aesthetic values in the design of data to sound mapping strategies (Barrass et al 2018). As such sonic information design is concerned designing mapping strategies which can contribute to making a given data set meaningful. This central concern with meaning–making is also reflected in embodied cognition research practices. While the study of meaning–making has generally focused on linguistics and semiotics (excluding meaning-making in aesthetic experience), embodied cognition researchers address meaning-making and aesthetics and have presented strong evidence for the argument that meaning–making and aesthetic experience are underpinned by the common apparatus of embodied of cognition (Johnson 2010, 2017; Varela *et al.* 1991; Núñez and Freeman 1999). This concern with meaning–making suggests that embodied cognition might provide useful insights into the manner in which sonification can be used to make meaning of complex and difficult–to–represent data.

However an embodied cognition approach to sonification may also be useful in a number of other contexts. Many researchers have argued that some open challenges in the field of auditory display include a need for a comprehensive account of the cognitive processes at work during sonification listening (Vickers 2012; Neuhoff 2011; Grossman 2010; Worrall 2009; Neuhoff and Heller 2005; Walker and Kramer 2004) and a need to embrace the aesthetic and creative aspects of sound for representing data (Barrass 2012; Barrass and Vickers 2011; Serafin et al 2011; Vickers and Hogg 2006; Vickers 2005). An engagement with embodied cognition has the potential to offer approaches and frameworks to support these goals; the problem of listening modes and aesthetic engagement during sonification listening highlights important issues for the efficacy of sonification approaches beyond the provision of meaningful framings (e.g. what types of listening and interaction contexts will support listener engagement).

Section 2: An Embodied Cognition Primer for HCI researchers

Embodied Cognition: Historical Roots

Embodied cognition is a research theme which arose to prominence in the late 20th century as discontent grew with the growing inability of more purely computationalist approaches in cognitive science to offer adequate descriptions of emotion, culture and aesthetic experience and, most critically, for how symbols on the mental layer posited by traditional cognitive science researchers —see (Gardner 1985)—are assigned their meaning. The traditional computational model of the mind was first codified in 1967 by Hillary Putnam (Putnam 1967) as the *classical computationalist theory of mind* (CCTM) and further refined in the work of Fodor (1975) and in Newell and Simons (1976) *physical symbol systems hypothesi*s. It claimed that the human mind was an information processor and that thought was a form of computation. Mental content, thoughts and perceptions were rendered as symbols, and thinking was conceived of as the rule–based processing of those symbols. But by the early 1980s, research approaches in psychology, cognitive science and computer science underpinned by the CCTM had attracted harsh criticism from a number of quarters. Even prior Putnam's foundational work, Ryle (1949) had presented the argument that computation could not simulate intelligence, as any mental symbol must be derive its meaning from a prior mental symbol, *ad infinitum*, concluding in what later critics have termed, *Ryle's regress*. Dreyfuss (1965), in the context of cognitive science and artificial intelligence, argued that symbolically mediated cognitive processes require a context of tacit and informal background knowledge against which to become meaningful, and that because the majority of human knowledge is non–formalisable, computation alone cannot account for human–level intelligence. A decisive 'no confidence' vote in the theoretical domain arguably came with Searle's (1980) 'Chinese Room' problem, which showed that whilst rule–based computation was sufficient to pass the Turing test, it was not sufficient enough to describe human understanding thus revealing some of the shortcomings of computationalism as a description of human–level cognition. Harnad (1990) would later formalise this question of how symbols acquire meaning as the *symbol grounding problem*, and while traditional computationalist models of the human mind could not solve the symbol grounding problem, an embodied cognition approach which grounds conceptual content in bodily experience could (Glenberg & Robertson 2000; Vogt 2002; Steels 2008; Barsalou 2010).

Thinking stemming from embodied cognition has led to compelling conceptual developments in a number of sonification–related disciplines , e.g. computer science, artificial intelligence and human computer interaction (Brooks 2003; Dourish 2004; Imaz and Benyon 2007), computer music (Leman 2008; Klemmer et al 2006), cognitive sciences (Varela et al 1991), visual perception (Noë 2009), aesthetics (Johnson 2013, 2017), music theory (Godøy 2006; Zbikowski 2005; Brower 2000; Larson 2012; Cox 2001), and linguistics and philosophy (Lakoff and Johnson 1999). Leading embodied cognition researchers (Johnson 1987, 2008, 2010, 2013, 2017 Johnson and Rohrer 2007; Maturana and Varela 1987; Varela et al 1991) take as a central point of their arguments that the mind–encounters the world through the intermediary of the human body and so cognition and meaning making are mediated and shaped by bodily interactions with the environment.

Embodied Cognition: Conceptual and Philosophical Underpinnings

Where Gibson (1977, 1978) explored how the environment may be considered to shape perception (and, arguably, 'lower–level' cognition), embodied cognition is more concerned with the manner in which 'higher–level' cognition of conceptual relationships is mediated by the interactions between the human body and its environment and, perhaps, between various conceptual structures which have been 'imported' from familiar bodily and environmental structures (Lakoff and Johnson 1999). Johnson (2007) presents a comprehensive theory that accounts for symbolic, linguistic and conceptual meaning, and also the kinds of meaning associated with emotions, felt qualities of experience, and aesthetic experiences of art and music. Johnson and Rohrer (2007) claim that the 'evolutionary embeddedness of the organism within its changing environments, and the development of thought in response to such changes, ties mind inextricably to body and environment.' This builds on the work of Varela *et al* (1991), who present the similar argument that meaning emerges in the reciprocal relationship, termed structural coupling, between organism and environment, as organisms evolve bodily–mediated minds to aid in effectively asserting themselves in their environments. In this view, any cohesive account of meaning-making must take the role of the body into account, because meaning-making is mediated by the human body and emerges in the interaction between that body and its environments. Johnson (2013) refines his definition of meaning making further in the argument that the meaning of an event, object or symbol is defined in relation to any bodily mediated past, present and possible future experiences it offers a subject.

Critical to this theory of meaning-making is the philosophy of *experientialism* or *experiential realism* (Lakoff and Johnson 1980): the claim that experience is the source of all meaning and, as a result, no meaning can exist in a form that is abstracted or separate from experience. This provides a middle ground between objectivist and subjectivist, materialist and idealistic, conceptions of knowledge and meaning. It rejects the idea that knowledge exists independently of the human mind and that perceptual and mental content is meaningful only to the degree that it accurately represents its real world counterpart. It also rejects the opposite view view that knowledge is a purely mental phenomenon and so a person can assign any meaning they choose to perceptual and mental content. Dichotomies between material and immaterial, subjective and objective are rendered meaningless in the experientialist context. This embodied understanding of knowledge and meaning-making relates closely to Husserl's (1913) *lebenswelt*, Heidegger's (1927) *dasein*, Dewey's (1934) 'lived experience' and Merleau-Ponty's (Ponty 1968) *chiasm* and Tode's (2001) thesis that the human body is the material subject of the world. In this approach perceptual and mental symbols, sonic or otherwise, become meaningful when they are associated with, and grounded in, embodied experiences (with reference to which they can be understood).

Embodied Metaphors and Meaning–Making Faculties

Theories of embodied cognition have described a number of cognitive meaning–making faculties thought to emerge in the shared relationship between similarly embodied organisms and environments. *Embodied image schemata*, first discussed by Johnson (1987) and Lakoff (1987) and further refined by Johnson and Rohrer (2007) as commonly shared fundamental gestalt patterns derived from recurrent patterns of bodily experience that provide people with a common basis for organising their experience, meaning-making and reasoning. They provide a basis for reasoning and inference by imposing their own unique logical syntax on chaotic raw experience independent of and prior to conceptualisation and language. For example Johnson's *source–path–goal* schema (Johnson 1987) describes the pattern shared by experiences in which a *trajector*, an entity that follows a trajectory, departs from a source and moves along a path towards an ultimate goal. According to the logic of the source-path-goal schema the source always precedes the goal and in order to reach a goal a path must be traversed. From this it can be reasoned that if a *trajector* is on the path then it has departed the source and is not yet at the goal and if a *trajector* is at the goal it can be reasoned to have departed from the source and traversed the path. These logical syntaxes organise experience into meaningful relations and can be used to lend structure to unfamiliar conceptual domains. In recent years they have be used in the design of intuitive computer interfaces (Imaz and Benyon 2007; Hurtienne and Blessing 2007). There is support for the claim that certain embodied schemata are common to large populations of people at a pre-linguistic level (Hampe 2005; Johnson 2013; Lakoff and Johnson 1999; Lakoff 2012).

The concept of *mapping* appears repeatedly across the embodied cognition literature (Lakoff and Johnson 1999; Fauconnier and Turner 2002). It is used to associate content from one mental space (a broad domain of related embodied schematic knowledge), or domain of embodied human experience with content in another. It is the basic process by which perceptual and conceptual symbols are assigned meaning. For example in the concept of a 'red herring', the concept 'red' is mapped from the domain of colour onto the concept of a 'herring' from the domain of 'fish', and for a person who is aware of the cultural connotations of the term, the concept of 'decoy' is also mapped onto the red herring.

Conceptual metaphors are a specific type of *cross-domain mapping* in which embodied schemata from familiar areas of experience, termed source domains, are mapped onto unfamiliar target domains that would otherwise be meaningless or unknowable, in order to make them meaningful (for further details see Lakoff and Johnson 1980). A classic example of a conceptual metaphor is the *LOVE IS A JOURNEY* metaphor in which the source-path-goal schema underlying a subject's experiences of journeying is mapped to lend familiar structure to the abstract concept of love. This allows 'love' to be conceptualised as a journey with a beginning, middle and end, where the lovers are travellers on a common path along which they may encounter difficulties and perils. In an embodied conceptual metaphor, the source domain provides a grounding within the embodied schemata of sensorimotor experience (Lakoff and Johnson 1980).

The concept of the *conceptual integration network* or *blend* was introduced by Fauconnier and Turner (2002) to describe how new structures of meaning can be created from basic embodied schemata during acts of creative and artistic thinking. A blend cross–maps conceptual content and embodied schemata from one mental space to another, thereby creating entirely new mental content that represents a blend of the content in the input spaces; for a more detailed analysis see (Fauconnier and Turner 2002). For example the mythical concepts of the Pegasus and Centaur have been described as blends between the concepts of a bird and a horse and the concepts of a man and a horse respectively (Martinez et al 2012). It is argued that such conceptual metaphors, mappings and blends are more than useful tools for interpreting and understanding the world, but are the faculties by which the experience of any intelligible world at all is made possible (Lakoff and Johnson 1999; Fauconnier and Turner 2002). Indeed, empirical studies—discussed in (Lakoff 2012)—have shed some light on the neural underpinnings of these cognitive faculties. They show that embodied schemata, conceptual metaphors and conceptual blending recruit neural networks in the human brain and sensorimotor system which are associated with bodily perception and action to perform a sensorimotor mimesis of the patterns of neural activity associated with gesture, perception and proprioception within the nervous system (*ibid*.).

Lakoff and Johnson's *embodied image schema* theories offer a range of conceptual metaphors which may be of particular utility in HCI contexts. The aforementioned *source–path–goal* model encapsulates a key modality within interactions. Indeed, this prototypical action/interaction is described in strikingly similar terms by Buxton (1987), who focuses on the *path–goal* stages in his *pursuit–tracking* and *target–acquisition* models of an action in an interaction design context. This path-based of centric/targeting relationships also relates to many of the key embodied image scehmata proposed by Lakoff and Johnson (see figure 1, below): *centre–periphery* (i.e. a given target as centre), *containe*r (targeting region as a distinct space 'containing' a particular function or set of functions), etc. Indeed, Buxton (*ibid*.) and Wanderley and Orio (2002) also highlight cases of constraints which include both linear path–goals, and *constrained circular motion* (akin to a *cycle* schema within Lakoff and Johnson's typology). Although Buxton's typology was advanced during an earlier phase of HCI (when WIMP–based interfaces were the state–of–the–art), the importance of arrangement of interfaces based on blending spatial and embodied functional logics can only be reinforced within the context of touchscreen and gesture–tracking–based interfaces. Indeed, Wessel and Wright (2001), writing in the context of computer music performance systems, have specifically invoked the typologies of Lakoff and Johnson, particularly in target–based (*drag–and–drop*) and cyclical/iterative (*scrubbing*) contexts.

PLACEHOLDER FOR FIGURE 1. Filename RoddyBridges-Fig1.tiff

Figure 1: centric/targeting schemata from Lakoff and Johnson (centre-periphery and container), alongside cycle schema (constrained cyclical, iterative motion); c.f. Buxton (1987); Wanderley and Orio (2002)

Section 3: Embodied Sonic Meaning Making for Sonic Information Design: current models and potential applications.

Having introduced embodied cognition and explored how research from embodied cognition may relate to key topics in HCI in general and auditory display and sound–based interaction in particular, this section will explore particular frameworks which may be applied in this context. It will address the problem from the twin perspectives of the affordances of interaction gestures and mapping forms, on the one hand, and the affordances of sound in perceptual and cognitive contexts, on the other. The discussion will be informed by a variety of interdisciplinary perspectives beyond embodied cognitive science, including research within cognitive musicology and theories and practices within electroacoustic/electronic/post–digital music composition.

Applications of Embodied Cognition Theory in HCI and Auditory Display

The first wave of HCI in the 1980s has been criticised for designing users out of their systems (Bannon, 1991). Card, Moran and Newell's (1986) *model human processor*, drove the adoption of *programmable user models* (PUMs), as tools for evaluation in HCI research. Consistent with

Newel's disembodied concept of cognition discussed previously, PUMs accounted exclusively for the classic computational theory of mind and resulted in the development of systems designed solely for the users' 'rational' information processing faculties, which were severely limited in their usability (Bannon & Bødker 1989). Bannon (1991) discusses how frustrations with these approaches led the second wave of HCI to shift in focus from 'from human factors to human actors' exploring situated and user-centric approaches and placing empirical testing of real users above the theoretical projections from generalised models. The third wave represented a further maturation of the second integrating something of an embodied turn (Dourish, 2004) which according to Bødker (2015) challenged 'the values related to technology in the second wave (e.g., efficiency) and embraced experience and meaning-making' as technology 'spread from the workplace to our homes and everyday lives and culture' a sentiment echoed by Harrison et al (2007).

Imaz and Benyon (2007) present an embodied approach to HCI design where image schema, conceptual metaphors and conceptual blends are exploited in the design of more user-friendly technologies. Hurtienne (2009) adopts an empirical approach in his exploration of the efficacy of image scehmata for conveying abstract information in user interfaces and their practicability as a design language for designing intuitive use finding image schema to be effective in both regards. Macaranas et al (2012) make a similar study of image schema and conceptual metaphors in tangible user interfaces, and Waterworth and Riva (2014) extend Imaz and Benyon's work to the domain of blended physical-virtual reality. Bødker and Klokmose (2016) offer guiding principles for more fully exploiting the potential of conceptual blending in HCI design.

Embodied cognition has been explored and applied in the context of a number of auditory display contexts. *Sonic interaction design* (SID) is the study of interaction in the context of auditory display. Research in this area draws heavily from Dourish's (2004) concept of 'embodied interaction' as the creation, manipulation and sharing of meaning through engaged interaction with artifacts. Dourish's views are influenced by the embodied phenomenology of Mearleau–Ponty and a consideration of meaning-making in an interaction context. As such embodied interaction is rooted within a phenomenological understanding of embodiment that focuses on the import of bodily movement to meaning-making. It differs from the cognitive science based approach discussed in this chapter in that it is focused on bodily interaction rather than the cognitive faculties involved in sonification listening. Embodied interaction has become the dominant paradigm for sonic interaction design research (see DeWitt & Bresin 2007; Polotti, Delle Monache, Papetti & Rocchesso 2008; Kabisch, Kuester & Penny 2005; Rocchesso & Bresin 2007; Bovermann, Hermann & Ritter 2006; Rocchesso, Polotti, Delle Monache 2009; Wakkary et al 2005, Droumeva & Wakkary 2008; Droumeva, de Castell & Wakkary 2007).

Whilst embodied interaction addresses meaning–making an interaction context, it does not account for how sound might exploit embodied cognitive meaning-making faculties for sonification. In recent times a number of researchers have begun to build upon the embodied interaction framework by introducing design principles informed by some of the cognitive faculties discussed previously. For example Antle et al (2011) apply embodied schemata and conceptual metaphors to link sound and interaction to support reasoning in an interactive sonification system. Breaking from the sonic interaction design paradigm and focusing more heavily on the sonic aspect of auditory display, Brazil & Fernström (2006) draw from conceptual metaphor theory and Varela et al's (1991) conceptual framework for embodied cognition to explore the recognition of concurrent auditory icons. A number of researchers have taken the embodied approach further by exploring and applying principles from embodied music cognition to auditory display. Embodied music cognition is a field at the intersection of systematic and cognitive musicology in which researchers offer systematic descriptions of how music works which are grounded in results from embodied cognition research. Drawing from one such framework Leman (2008) Diniz et al (2012) have applied principles from this area to design easy to use interactive sonifications by exploiting the embodied cognitive aspects of musical meaning-making.

Environmental Models of Sound: Gestalt Psychology, Auditory Scene Analysis and Ecological Psychoacoustics

Gestalt psychologists, such as Rudolph Arnheim, who focused his research on the psychology of art, have created useful frameworks for thinking about and working with sound in an embodied context, derived from principles of organisation within an environment. Gestalt psychology was a school of thought on perception and cognition built around the central claim that the mind organises chaotic perceptions of reality (or a complex environment) into cohesive wholes where unified topological structure emerges on the basis of simple perceptual principles or laws (Köhler 1929, Koffka 1931, Wertheimer 1938). Central to the organisational laws of Gestalt psychology is the law of *Prägnanz*, which says the mind orders experience in a regular and systematic manner. Gestalt psychology has been extended to offer a systematic cognitive account of music perception on the basis of emergent meanings from gestalt structures (Leman 2008:30). Arnheim (1954) presented a theory of the balancing forces in visual aesthetics, suggesting that 'balance' and 'force' in a visual composition can be described by the juxtaposition of concentric grid patterns (centres) over a Cartesian grid pattern (the frame). The tension inherent in the juxtaposition of these gestalts manifests itself perceptually in terms of force, movement and balance. Arnheim (1984) expands this to the realm of Western art music, with musical 'meaning' (in the form of aesthetic dynamics of tension and release) emerging from the fulfilment or subversion of expectations motivated by the law of *Prägnanz* that arise in this musical discourse. Meyer (1956) presents a similar theoretical framework for the emergence of meaning in music, situating Dewey's concept of lived experience and conflict theory of emotions within the context of Gestalt–based meaning–making, with the mind deriving gestalts from environmental, embodied experience, which are then used to structure the listener's expectations of a musical piece. Similarly, Johnson's (2007) characterising of sonic (musical) organisation through metaphors which are not simply concerned with an individual body's relationships, but also those within the wider frame of an environment (his *music–as–moving–force* conceptual metaphor) can be seen as compatible with both the origins of Gestalt theories of aesthetics, and the details of their conceptual associations.

Another influential environmental (and Gestalt–influenced) model of perceptual relations within audio, one which has contributed directly to the ideas of many auditory display researchers, is Bregman's *auditory scene analysis* (Bregman 1990; 1994). Bregman (*ibid.*) describes describes how the auditory system applies the aforementioned Gestalt principles in ecological contexts to the organisation of streams of sound into perceptually meaningful patterns. Indeed, in an attempt to summarise these organisational (or *grouping*) principles, Bregman further traces the connection between these structuring principles and the environment by grouping them under the rubric of 'environmental regularities' (Bregman 1994), including concepts of grouping by timbral/textural similarity and related phenomena (such as grouping by pitch/frequency proximity) as being due to 'gradualness of change' in streams of activity within an auditory scene. Indeed, the introduction to (Bregman 1990, p.1) explicitly describes his broader approach and philosophy as being ecologically–based. Auditory scene analysis has drawn the interest of a large range of sonification researchers, and was originally recommended as a focus of perceptual and cognitive research in the field in the *1997 Sonification Report* (Kramer et al 1997), commissioned by the US National Science Foundation, and was again referenced as an important factor in sonification research in *The Sonification Handbook* (Walker and Nees 2011). A more complete review of projects which explore auditory scene analysis in sonification research is beyond the scope of this chapter, but nonetheless, the perspective of the affordances of sound's perceptual grouping principles as being related to environmental affordances can be seen as establishing points of compatibility with the broader perspectives of embodied cognition. In a similar fashion, Neuhoff's (2004) *ecological psychoacoustics* borrows heavily from the Gibson's ecological approach to perception which structured the premise that an organism's actions are constrained by the affordances granted by its environment. He expands this definition to view auditory perception and cognition as the result of complex physical, physiological, and cognitive factors. This definition does not account explicitly for the nature of human embodiment. Ultimately, ecological psychoacoustics is a framework for understanding sound on the basis of (embodied) *perception–action loops,* and both Lakoff and Johnson and Varela *et al* (1993) have engaged with Gibson's theory of affordances in developing their theories. Whilst Varela *et al* (*ibid.)* note that Gibson's approach is rooted n a theory of naive realism (the belief that reality is represented to the listener directly), the broad thrusts of the concept of the affordance originating within an enactive environmental–interaction context, is still nonetheless seen as compatible with an embodied cognitive theory of mind and meaning-making. This is of particular relevance for the present purposes given that Gaver (1989) draws upon

Gibson's theory of affordances to develop the *auditory icon*, a sonification technique that maps data to familiar everyday sounds, and Walker and Kramer (2004) also recognised the importance of an ecological approach to sonification.

Embodied Cognition and Cognitive Musicology

Reconsidering sound organisation from the perspective of ecologically–grounded perception and cognition may offer insights into the structural dynamics and meaning-making within the broader contexts of sonic interaction design and sonification. In a broadly similar fashion to the musical model of Johnson (2007), recent years have seen an engagement on the part of musicology (music theory) with principles and theories derived from embodied cognition. Cognitive musicologists such as Steve Larson (2012), Candace Brower (2000), Lawrence Zbikowski (2005), Arnie Cox (2001) and Jason Wyatt Solomon (2007) have all offered in-depth treatments of music in terms of embodied schemata, metaphors, graded categories etc. Larson (2012), Brower (2000) and Zbikowski (2005) each have a specific bent towards a top-down understanding of musical discourse in an EC context. Cox (2001) and Solomon(2007) focus on a *bottom–up* description, intended to demonstrate how music is built up from embodied experiences. Johnson's contributions seek to unite the two approaches. Cox achieves his aims through his *mimetic hypothesis*; see also (Godøy 2003). This suggests that listeners make sense of sounds by relating them to previous sounds they have made through a process of imitation at the sensorimotor level. Cox demonstrates how music cognition is intimately bound up with sensorimotor stimulation which provides the basic "physical" process by which musical meaning is enacted in the form of embodied schemata and embodied metaphors. His theory would go on to influence that of Johnson (Johnson & Larson 2003). Solomon maintains a focus on spatial gesture and attempts to build an EC framework to explain the spatial aspects of musical forces in terms of embodied cognitive skills, from that angle. Brower (2000) relates meaning and syntactical structure in Western tonal music to physical forces that act upon the human body, gravity for example, by way of embodied schemata and conceptual metaphors (directly referencing the schemata of Lakoff and Johnson). Larson expands his focus to three musical forces, gravity, magnetism and inertia that emerge from the inferential structure of embodied conceptual metaphor and embodied schemata.

Zbikowski (2005) demonstrates how harmonic music is understood at a basic level in terms of graded categories of musical events, in which prototypical members and their graded counterparts give rise to a unique syntax within a piece of music. Meaningful musical discourse can then unfold through the metaphorical cross–domain mappings that project embodied schemata into those category members (such as motives and rhythms) to root their meanings in terms of our embodied experiences. One category member may also blend with either another musical category member or extra-musical concept, and these blended spaces as well as the spaces elaborated through cross-domain mappings may be built up through more mapping to generate conceptual models. The inferential aspect of this blending leads to new understandings of one category member in terms of another. Through metaphorical mappings between schemata, categories and blends one can understand what it means for a passage to rise and fall or become choppy and then flow. According to Zbikowski (2002), and Lakoff and Johnson (1999), human auditory perceptual space is organised in terms of embodied schemata mapped across from other domains by processes of cross domain mapping, metaphorical projection and blending. Without cross–domain mappings of embodied schemata, music and auditory dimensions would not simply be meaningless, but would cease to exist in any cognisant way for the listener. Following this argument, it is only through the mapping of embodied schemata to the auditory domain that auditory attributes become cogent and meaningful. This has considerable implications for auditory display and suggests that meaningful sonification mapping strategies require consideration of the structures, originating contexts and conceptual associations of these embodied schemata and any associated blends within the domain of sound perception.

Auditory Imagery and Gestural–Sonorous Objects in Sound Environments and in Music

If sonic meaning is related to environment–derived embodied schemata, the manner in which we conceptualise sounds and their relationships becomes a crucial point of focus for the auditory display and sound–based HCI researcher. The manner in which these schemata are constructed with particular reference to sound as a sensory and environmental modality, therefore requires particular attention. In this regard, the study of *auditory imagery* may support the extension of embodied image schema theory into the sonic domain. An *auditory image* is any imaginatively generated sound experience that happens in the absence of an acoustic stimulus (Intons-Peterson 1992). It is a near ubiquitous and highly systematic phenomenon which can be quite rich and vivid. The term image refers to the imaginative process rather than the visual medium, and auditory imagery is imagined sound not an internal visual picture of a sound. A large amount of everyday auditory experiences are of auditory imagery in the form of sub-vocalisations, musical recount, the phenomena where one mentally re-enacts a piece of music. Armstrong, Stokoe and Wilcox (1995) describe how subvocalisation, a specific form of auditory imagery, acts as a kind of mimetic simulation of physical gestures in the vocal domain. Cox (2001) shows that this mimesis is a critical process for musical meaning-making and describes how subvocalisation is an embodied process that provides the some of the underpinnings for auditory imagery. Further studies have used fMRI data to reveal that auditory imagery involves the simulation of auditory cognition in many of the brain areas associated with auditory perception (Halpern et al 2004, Hubbard 2010). Kiefer et al (2008) have shown that both thinking about, or the conceptualisation of, acoustic features reinstates the same patterns of brain activity present during the perception of similar acoustic features. Godøy (1997) offers a good account of how auditory imagery is grounded in bodily action by Lakoff & Johnson's embodied schemata and the role that auditory imagery plays in the meaning making process. In an auditory display context, auditory imagery has been explored as a key meaning-making mechanism in sonification (Nees and Walker 2008; Nees 2009; Nees and Walker 2011; Nees and Best 2013).

In a similar fashion (and even closer to the discourse of embodied image schema theory), Godøy (2006) proposes the *gestural–sonorous object* as an extension of Schaeffer's sound object (*objet sonore*). He argues that Schaeffer 'applied fundamental schemata of bodily experience to sound perception.' As a result Schaeffer's original framework of typological and morphological categories for sound objects are all built around sound producing physical gestures. These gestures then become abstracted as image scehmata on the basis of which sound objects are gesturally encoded in the human mind. Godøy (*ibid.*) further builds upon this embodied image schematic aspect of the sound object incorporating embodied aspects of Smalley's (1986 1997) framework to more comprehensively account for embodied meaning–making in terms of gestural sonorous objects. A number of researchers and designers have explored and applied Godøy's framework in the context of embodied approaches to sonification design (Tuuri 2009; Jensenius & Godøy 2013; Grond 2013; Worrall 2014; Barrett 2015; Siebert et al 2015).

Beyond typologies for individual sound–gestures, Smalley’s theory of (1986 1997) *spectromorphology* (derived from sound spectrum and morphology) is an analytical framework for electroacoustic music (music based on both electronic materials and electronically–processed recordings) which advances a model for how timbres, textures and *groups of sounds* may interact dynamically in perceptual, aesthetic and conceptual terms. This model deserves particular attention here because it displays some striking resemblances to the cognitive competencies of embodied cognition, and accounts for sonic experience within composed contexts which utilise materials and structures which are analogous to ‘natural’ sound environments. The theory of spectromorphology was an extension of Schaeffer’s (1966) *objet sonore* at the level of the perceived sonic footprint across the same dimensions as the spectrogram: frequencey and time. In retrospect Schaeffer’s objet sonore has been shown to classify sound in terms of ‘embodied’ categories (Godøy 2006). In developing Schaeffer’s ideas into spectromorphology, Smalley has created an in–depth taxonomy for the embodied structure of auditory space. The framework relies on categorisation schemes that derive from ‘primal gestures extrinsic to music’ (Smalley 1997), and is discussed using a framework which uses a language of gestures and forces. This would suggest that spectromorphological shapes are extensions of embodied schemata in the auditory domain. It is suggested here that embodied schemata provide the structure for the primal gestures upon which spectromorphology rests. Many of the dynamic structures described in spectromorphology bear striking resemblance to the dynamic structures of embodied schemata described by Johnson (1987), and Johnson (2007), with the compatibility being clarified further in Johnson’s (*ibid*.) proposal of the *music–as–moving–force* conceptual metaphor.

Similar observations of the similarity between embodied schemata and spectromorphology have been made by Graham and Bridges (2014, 2015; Graham et al 2017). Specifically, Johnson’s (2007) typology of *qualitative dimensions of movement* (and, hence, within this line of argument, conceptual structures), includes the dimensions of *tension, projection and linearity*. These dimensions deal with the connection between the manner of the movement's initiation and the form of the resulting gesture. Graham and Bridges (2014) highlighted the striking resemblance that this model bears to Smalley's (1997) account of the implied *energy–motion profiles* of individual sound events or groups of sound events within his theory of spectromorphology, see table 1, below.

Johnson (2007): *qualitative dimensions of movement*	**Smalley (1997): *energy–motion profiles***	**Embodied meaning/association**
Tension	Motion rootedness	force/rate–effort=>overcoming inertia
Projection	Motion launching	Sudden rate-change / transient movement
Linearity	Contour energy/inflection	Coherence of path

Table 1: Comparison of Johnson's dimensions of movement with Smalley's energy–motion profiles and embodied associations; after (Graham and Bridges 2014)

Tension and *motion–rootedness* are correlated with an embodied expectation (force–dynamic) of the effort required to overcome inertia: the persistence of a system's grounded/stable state. *Projection/motion–launching* implies that a significant application of force may instigate a large–scale movement, the degree of which may dictate the form that the continuing gesture's *linearity/contour–energy* takes (e.g. a more coherent or incoherent path). Given the broad correspondence, these theories may be fruitfully combined to contribute a shared framework for mappings within auditory display and sonic interaction design.

This corollary of an embodied cognitive model based on a metaphor of moving objects and forces draws our attention to the manner of execution of a particular embodied image schema in the context of interaction and mapping. For example, a source–path–goal schema may be initiated via a motion that requires greater effort to overcome inertia. Projection denotes an extremely energetic movement such as a sudden rate–change movement with less inertia that results in an event that continues to sustain itself for a longer period of time. Linearity denotes whether a resulting path is more coherent and incoherent, relating to the manner of its execution. Thus, certain regions within the temporal evolution of a sound event (or stream of sound events) within a sonification may be framed as meaningful based on localised variations upon an overall structural trend. In the context of HCI, interaction based on centre/periphery models can also be informed by force/inertia dynamics, with velocity of an interacting gesture treated as a surrogate for force (e.g. MIDI, many touchscreen applications, Lemur, etc.). Moreover, Graham and Bridges (2015; Graham et al 2017) have proposed ways in which these embodied frames ('embodied narratives') may align with the three–dimensional timbre–space relationships uncovered by Grey (1977), combining the more straightforward embodied associations of a verticality schema (within spectral centroid position), with ideas of spatial/timbral presence (presence or absence of attack transients) and degrees of 'dynamism or inertia' (fast or slow temporal evolution/envelope profiles). These relationships are outlined in figure 2 and table 2, below.

PLACEHOLDER FOR FIGURE 2. Filename RoddyBridges-Fig2.tiff

Figure 2: applying embodied–cognitive rubrics to the classical three–dimensional timbre–space model of Grey (1977); from (Graham et al *2017); image © B. Bridges 2017*

X axis: Dynamic 1: ***Temporal Synchronicity of Attack Envelopes***	X axis ranges from *motion launching* (rapid dynamic change, more synchronous entry) to gradual *contour energy* (asynchronous entry of partials).
Y axis: Dynamic 2: ***Spectral Energy Distribution: Height vs. Rootedness***	Y axis via the spectral centroid gives us two parallel scales and dynamics: *contour energy* (verticality schema: pitch height) and associated *motion rootedness*; regions of stability.
Z: axis: Dynamic 3: ***Spatial Clarity within Individual Sound Sources***	Z via presence or absence of attack transients articulates *motion rootednes*s or *tension* (audible transient products of inertia) to ungrounded events (diffuse or sustained tones). This is related to a *diffuse–to–point source* spatial coverage schema.

Table 2: Dynamics within the three dimensions of this embodied timbre–space model; after (Graham et al*, 2017).*

A number of auditory display researchers have recognised and explored the close relationship between electroacoustic music practices and sonification (Vickers 2005; Vickers 2006; Barrass and Vickers 2011; Fencott and Bryan-Kinns 2009; Worrall 2013; Miranda, Bonet and Kirke 2016). Diniz (2012) draws heavily from spectromorphology and embodied music cognition, as developed by Leman (2008), to develop an empirically grounded conceptual framework and related technological implementation (JOINDER) for non-verbal sound communication within the domains of interactive sonification and musical composition. Diniz is concerned with the important role that interaction in top-down and bottom-up cognitive processes. As such, his framework uses spectromorphology to inform the design of data to sound mapping strategies where the data is derived from from technologically mediated spatial explorations and aims to provide a "human centered foundation for the design and implementation of more efficient tools within the auditory display and musical production community." Drawing from a number of similar threads to those discussed in this chapter, Barrett (2015) adopts an embodied cognition approach to sonification which integrates Godøy's gestural sonorous object framework with Cox's (2001) mimetic hypothesis and the concept of surrogacy from spectromorphology (Smalley 1986). This is undertaken in the context of the development of an interactive parameter–mapping 3D spatial sonification program called Cheddar (Barrett 2015).

Embodied Cognition and Solutions to the Mapping Problem in Auditory Display

We now return to the central issue of the mapping problem within auditory display and related applications. As noted earlier, this is a key problem within both auditory display and general sound–based HCI contexts. In the field of auditory display, Flowers (2005) has highlighted the central importance of this problem with the observation that, in his experience, 'meaningful information does not necessarily arise naturally when the contents of complex data sets are submitted to sonification'. Framed in this way, the mapping problem asks how data can be mapped to sound in a way that presents the data to a listener in a meaningful manner. Worrall (2009) suggests that the mapping problem poses a significant challenge to the effective application of more orthodox parametric sonification approaches such as *parameter mapping sonification* (*PMson*) . The present chapter considers the mapping problem in auditory display from two primary perspectives. The first is the question of how to consciously design mapping strategies which foreground frameworks which can support the effective communication of data to a listener and the second, which is often referred to as *dimensional entanglement* (Worrall 2010; 2011; 2013), is concerned with the intermingling of auditory dimensions traditionally assumed to be separable within traditional parametrically–based sonic frameworks (such as *PMson).* For example while pitch, loudness, duration and timbre can be mapped to unique data these dimensions are not independent. Changes in one dimension can cause changes in another obscuring the intended data to sound mapping strategy and making it difficult for the listener to interpret a sonification (see Grond and Berger 2011; Peres and Lane 2005; Flowers 2005; Worrall 2010; Peres 2012). It has been argued that this aspect of the mapping problem is a result of the way sound is parameterized by sonification designers (Roddy 2015). Dimensions adopted from conceptual paradigms discussed previously, in which a computationalist understanding of knowledge and meaning, wherein the listener is a computer of abstract perceptual symbols which reveal their meaning through computational processing on a mental level supposedly devoid of any real link to or grounding in embodied experience, cannot account for how humans make and assign meaning. While such dimensions are useful for describing and measuring sound in terms of the acoustic waveform, and its perceptual correlates, they are not necessarily useful dimensions for communicating information in a sonification context. Truax (1984) argues that the prevailing common sense understanding of sound in the West is built around a model of energy transfer. In this model the energy of physical excitations are transferred to physical waveforms that are in turn transferred to sonic experiences in the mind of the listener. He argues that this model is adequate for quantifying sound in terms of physical phenomena but is not sufficient for describing how sound communicates information to a listener. Wishart (1996) makes a similar argument about Western art music. He reasons that as Western art music evolved the focus of composers shifted from creating and organising musical performances to creating and organising written scores. This reduced the rich multi-dimensional spectra of musical discourse to just three primary dimensions:

pitch, duration and timbre. These dimensions represent a small sub-set of the many possible dimensions of sonic experience. Worrall (2010) argues that this reductive approach to music is informed by the computationalist theory of mind and that modern music technologies employed to create sonifications are built around this same disembodied framework which fails to account for the role of the embodied performer and the perceptual and cognitive configuration of the embodied listener. The reduction of the rich spectra of sonic experience to non-orthogonal dimensions of pitch, duration, amplitude and timbre, the appropriation of these isolated dimensions as the primary channels for communicating information to a listener and a disregard for the emb theodied perceptual and cognitive faculties of the listener in interpreting a sonification have all contributed to the mapping problem. In this context, new models of the dimensions of sonic communication are required for an embodied approach to sonification that might overcome the mapping problem. In the sonic information design paradigm, this need to find more communicative dimensions of sound for representing data becomes a practical design problem which must be solved whenever a designer designs a sonification. Similar principles from embodied cognition have already been successfully applied to help solve similar design problems in the context of HCI intuitive user centered visual interfaces (Imaz and Benyon 2007; Hurtienne and Blessing 2007) and tangible interfaces (Macaranas et al 2012) and can also be used to similar effect in auditory displays (Antle et al 2011).

A suggested framework for helping to design sonification solutions which address the mapping problem is the *embodied sonification listening model* (ESLM) (Roddy 2015), represented in figure 3. This model uses a conceptual metaphorical mapping to describe how listeners derive an understanding of the data from the sounds presented in a sonification. It introduces the *sonic complex* as a sonic metaphor for the *measured phenomenon,* e.g. a specific animal, and the *sonic dimension* as the sonic metaphor of the dimension of measurement in the data source e.g. the weight profile of that animal over time. The mapping from sonic metaphor to imagined data is mediated by the listeners embodied schematic knowledge. Designing sonification solutions on the basis of the model can help the designer to develop solutions which account for some the embodied cognitive components of sonification listening.

PLACEHOLDER FOR FIGURE 3. Filename RoddyBridges-Fig3.eps

Figure 3: The Embodied Sonification Listening Model from (Roddy 2015)

Conclusion: HCI, sonification, multi-modal aspects grounded by embodied cognitive frameworks

Whilst the wider field of HCI has benefited greatly from developments in embodied cognition research, auditory display its related sub-disciplines are in a position stand to further benefit from adopting an embodied approach. Frameworks from embodied cognition can help to design auditory display solutions which rise to the challenges posed by the sonic representation of complex multivariate data sets, e.g. the mapping problem and exploit the communicative potential of sound and sound synthesis techniques. They can also help to capitalise on the opportunities offered by a new wave of gesture–based controllers and interaction modalities. This chapter explores a number of such frameworks which, the authors argue, might be of use to researchers and designers working with sound in a HCI and auditory display context. In making the case for applying an embodied cognition approach to these problems, we note that HCI research has the potential to engage still further with this rapidly developing field. The authors believe that a broad interdisciplinary approach, integrating methodologies and expertise from cognitive science, philosophy, electroacoustic music practice and design, will support innovations within auditory display and sound–based HCI research and praxis.

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